Top Quark Mass Measurements at the Tevatron and the Standard Model Fits

M.H.L.S. Wang for the CDF and DØ collaborations
Fermi National Accelerator Laboratory,
Batavia, IL 60510, U.S.A.

New measurements of the top quark mass from the Tevatron are presented. Combined with previous results, they yield a preliminary new world average of $m_{\rm top} = 170.9 \pm 1.1(\rm stat) \pm 1.5(\rm syst)\rm GeV/c^2$ and impose new constraints on the mass of the Higgs boson.

1 Introduction

The huge interest in a precise measurement of the top quark mass ($m_{\rm top}$) is primarily motivated by its role in constraining the mass of the Higgs boson ($m_{\rm Higgs}$). To see this, let us begin by looking at the mass of the W boson (m_W) in the Standard Model which, when one-loop radiative corrections are included, can be related to well known electroweak quantities through the following expression:

$$m_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{\sin^2\theta_W\,(1+\Delta r)}. \tag{1}$$

The radiative corrections contained in Δr receive contributions from the top quark:

$$(\Delta r)_{\rm top} \approx \frac{3G_F m_{\rm top}^2}{8\sqrt{2}\pi^2}\frac{1}{\tan^2\theta_W} \tag{2}$$

and the Higgs boson:

$$(\Delta r)_{\rm Higgs} \approx \frac{11 G_F m_Z^2\cos^2\theta_W}{24\sqrt{2}\pi^2}\ln\frac{m_{\rm Higgs}^2}{m_Z^2} \tag{3}$$

where m_Z is the mass of the Z boson. From these expressions, we see that $m_{\rm top}$ enters quadratically while $m_{\rm Higgs}$ enters logarithmically. A precise knowledge of both m_W and $m_{\rm top}$ in combination with existing electroweak data is therefore necessary to impose useful constraints on $m_{\rm Higgs}$. Such constraints, in turn, are of tremendous value in the ongoing search for the Higgs.

In this talk, we present the latest top quark mass measurements from the CDF and DØ collaborations based on up to 1 $\rm fb^{-1}$ of Run II data collected at Fermilab's Tevatron. These results are combined with previous ones to give a new preliminary world average for $m_{\rm top}$ which, in turn, yields new constraints on the Higgs mass.

2 Measurement Channels and Experimental Challenge

Now that we understand the motivation behind a precise determination of the top mass, let us look at the top quark decay channels in which these measurements are performed and the experimental challenges they pose.

In the all jets channel, both W bosons from the $t\bar{t}$ pair decay hadronically into jets for a total of 6 jets in the event. This channel has the advantage of having the largest branching ratio of 44%. It suffers, however, from large background levels from QCD multijet events. On the other hand, it benefits from the presence of the hadronically decaying W bosons whose well known masses can be exploited to perform an in-situ calibration of the jet energies, reducing the effect of the systematic uncertainty in the overall jet energy scale. In the dilepton channel, both W bosons decay leptonically. It has the advantage of having the lowest background levels coming from Drell-Yan processes associated with jets, diboson production with associated jets, and W+3 jet events with one jet faking an electron. Unfortunately, it also has the lowest branching ratio of 5%. In the lepton+jets (ℓ+jets) channel, one of the two W bosons from the $t\bar{t}$ pair decays hadronically while the other one decays leptonically. This channel maintains a good balance between a reasonable branching ratio of 29% and moderate background levels from W+jets and QCD multijet events. Like the all jets channel, it can benefit from an in-situ jet energy calibration using the m_W constraint. It has traditionally yielded the most precise m_{top} measurements.

To appreciate the challenge involved in measuring the top mass at the Tevatron, let us now take the ℓ+jets channel as an example. In this case, what our reconstruction programs give us from the detector are several jets, a high p_T lepton, substantial missing transverse energy, and an interaction vertex. Since we don't really know how to associate jets with partons in general, all jet permutations need to be considered in a straightforward reconstruction of the top mass. Furthermore, unlike long lived particles, there are no detached vertices associated with the top quark itself that can be used to separate the signal from the background events. This means that, even with b-tagging, there are no sharp and clean mass peaks from which the top mass can be determined directly. Fortunately, despite these challenges, sophisticated measurement techniques have been developed that make a precise measurement of the top mass possible.

3 Top Quark Mass Measurement Techniques

In this section we describe the three major techniques used in measuring the top quark mass. All the measurements presented here use one or some combination of these techniques.

The template method is the oldest of the three techniques and has been used for most of the earliest mass measurements. In this technique, one begins by identifying a variable sensitive to the top mass, an obvious choice of which would be the kinematically reconstructed value of the mass itself. Distributions of the chosen variable are then plotted separately for several samples of fully simulated Monte Carlo (MC) events differing only in the value of the top mass used to generate the signal events. Each of these distributions is called a template and is associated with a particular value of the input mass. The top mass is then extracted from the data sample by comparing the data distribution directly with each MC template to find the best fit value based on some measure of the goodness of fit. More recent applications of this technique parameterize the templates in terms of a probability density function which is used to construct likelihoods from which the top mass is extracted.

DØ pioneered the application of the matrix element (ME) method to top quark mass measurements in the Run I data from the ℓ+jets channel[1]. It is based on calculating the probability for observing each event which includes contributions from both signal and background sources. The signal probability is calculated as a function of the assumed top mass, resulting in a prob-

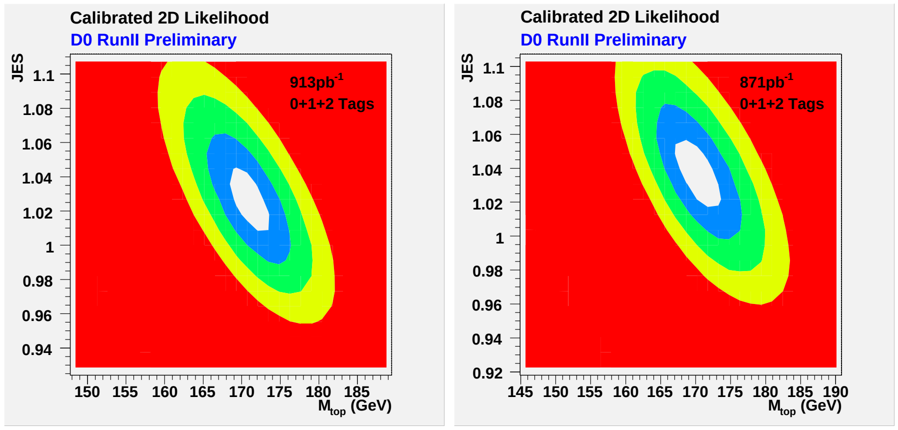

Figure 1: 2D likelihoods for electron and muon channels for the DØ ℓ+jets result.

ability distribution for each event. The probability is taken to be the differential cross section for the process in question. The calculated probability distributions for every event in the data sample are combined to construct a joint likelihood from which the top mass is determined and its uncertainty estimated. The ME method makes use of as many measured variables as possible to completely specify an event, thereby allowing maximum discrimination between signal and background events. Within each event, all possible jet permutations are combined in a natural way based on their relative probabilities. Furthermore, the use of transfer functions allows a probabilistic treatment of the mapping between parton and jet energies where the full spectrum of parton energies contributing to the observed jet energy is taken into account.

The ideogram method, like the ME method, calculates an event-by-event likelihood. This technique makes use of a constrained kinematic fit to reconstruct the top mass. Using a simple parameterization, the probability for observing the reconstructed mass is then calculated as a function of the true value with the measurement resolution taken into account. This technique, which was also pioneered by DØ [2], aims to achieve statistical uncertainties comparable to those of the ME method without requiring as many computational resources.

4 New Results from the Tevatron

DØ has measured the top quark mass in the ℓ+jets channel using the ME method described in the previous section [3]. This measurement takes advantage of the m_W constraint to perform an in-situ calibration of the jet energies. This is done by introducing a global scale factor, JES, that is applied to the energies of all the jets. A fit is then performed that maximizes the likelihood simultaneously in $m_{\rm top}$, JES, and the signal fraction C_s. The 2D likelihood fits in $m_{\rm top}$ and JES are shown separately for the electron and muon channels in Figure 1. The combined result for both channels is $170.5 \pm 2.4(\rm stat + JES) \pm 1.2(\rm syst) GeV/c^2$ for 0.9 fb^{-1} of data. Dominant systematic uncertainties are in the modeling of initial and final state radiations and b-fragmentation. This is the best DØ measurement of the top quark mass to date.

CDF has also measured the top quark mass in the ℓ+jets channel using the ME method. Like the DØ result, this measurement employs an in-situ jet energy calibration through the inclusion of a global JES parameter in the likelihood fit. The left plot in Figure 2 shows the 2D likelihood fit to the data for both electron and muon channels in JES and $m_{\rm top}$. The right plot in Figure 2 shows the expected error distribution from MC ensemble tests with the arrow indicating the measurement uncertainty. The measured result for 0.94 fb^{-1} of data is $170.9 \pm 2.2(\rm stat + JES) \pm 1.4(\rm syst) GeV/c^2$. The largest systematic uncertainty is in the modeling of initial and final state radiations. This is currently the most precise CDF measurement of the

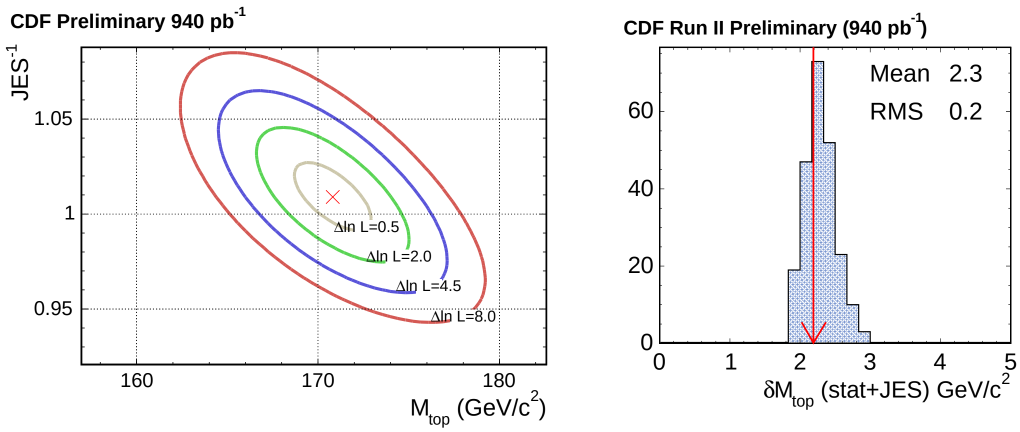

Figure 2: Likelihood fit to data and expected error distributions for the CDF ℓ+jets result.

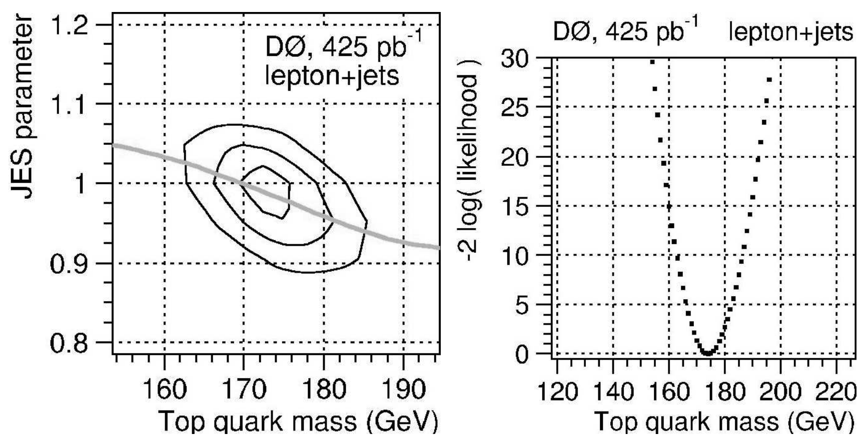

Figure 3: 2D and 1D likelihoods for the DØ ideogram ℓ+jets results.

top quark mass.

DØ has a measurement of the top quark mass in the ℓ+jets channel using the ideogram method [2]. Like the two results above, it employs an in-situ jet energy calibration. The 2D likelihood as a function of JES and $m_{\rm top}$ is shown on the left in Figure 3 with the gray line indicating the fitted value of JES as a function of $m_{\rm top}$. The right plot in Figure 3 shows the 1D likelihood as a function of $m_{\rm top}$ along the gray line in the left plot. The result for 0.4 fb^{-1} of data is $173.7 \pm 4.4(\mathrm{stat} + \mathrm{JES})^{+2.1}_{-2.0}(\mathrm{syst})\mathrm{GeV/c^2}$. Dominant systematic uncertainties are in the modeling of b-fragmentation and in the b/light jet energy scale ratio.

CDF has applied the ME method to a measurement of the quark top mass in the dilepton channel [5]. A plot of the probability as a function of $m_{\rm top}$ is shown on the left in Figure 4 and the expected error distribution on the right with the arrow indicating the measurement uncertainty. The result for 1 fb^{-1} of data is $164.5 \pm 3.9(\mathrm{stat}) \pm 3.9(\mathrm{syst})\mathrm{GeV/c^2}$. The systematic error is dominated by the uncertainty in the jet energy scale.

DØ has measured the top quark mass in the dilepton channel using a template method that assigns a weight to each neutrino solution based on the agreement between the calculated transverse momentum of the neutrinos and the observed missing transverse energy [6]. The result for 1 fb^{-1} is $172.5 \pm 5.8(\mathrm{stat}) \pm 5.5(\mathrm{syst})\mathrm{GeV/c^2}$. The dominant source of the systematic error is the jet energy scale uncertainty.

CDF has measured the top quark mass in the all jets channel using a combination of template and ME methods [7]. Instead of using the ME method directly to measure the top mass, the value

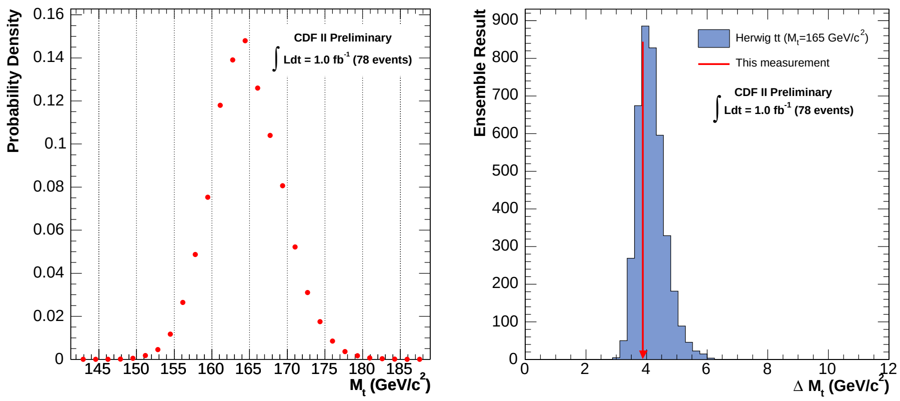

Figure 4: Probability and expected error distributions for the CDF dilepton result.

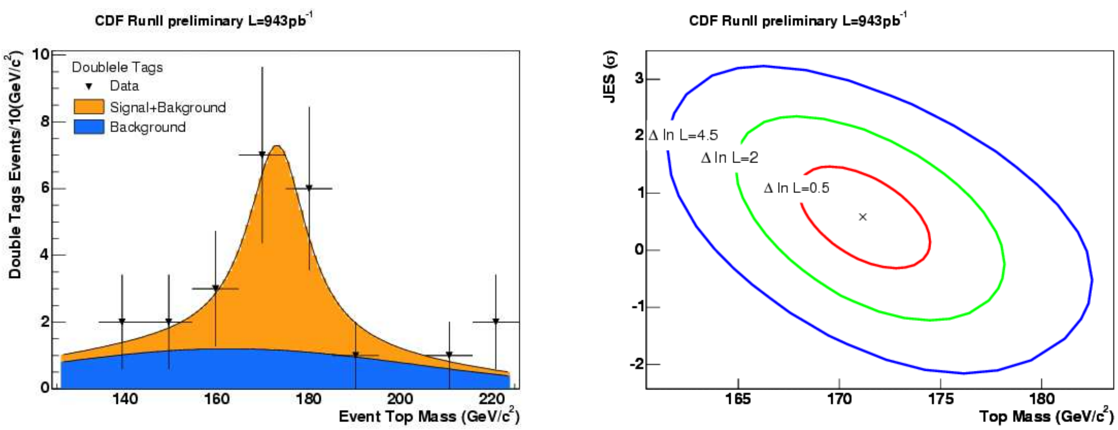

Figure 5: Data/MC distributions on the left and mass/JES contours in data on the right for CDF all jets result

determined from the method is used to construct the MC templates. Probabilities calculated from the ME are also used in the event selection process to identify events with high signal probability. This result also uses the m_W constraint to perform an in-situ jet energy calibration. The left plot in Figure 5 shows a fit of the data distribution to the MC templates for events with two b-tagged jets. Contours of JES and $m_{\rm top}$ in data are shown on the right in Figure 5. The result for 1 fb^{-1} is $171.1 \pm 3.7(\rm stat + JES) \pm 2.1(\rm syst) GeV/c^2$. The largest systematic uncertainties are in the simulation of fragmentation and showering and of final state radiation.

5 New World Average and Standard Model Fits

From above, the best result of each experiment in each channel is combined with previous results yielding a new preliminary world average [8] of $m_{\rm top} = 170.9 \pm 1.1(\rm stat) \pm 1.5(\rm syst) GeV/c^2$ shown on the left in Figure 6. The ME ℓ+jets results from DØ and CDF carry the largest weights in this average of 40% and 39%, respectively. This value is 0.5 GeV/c^2 lower than the previous world average. With this new preliminary result, the top quark mass is now known to a total uncertainty of 1.8 GeV/c^2 corresponding to a relative precision of 1.1%.

This new top quark mass is also combined with other precision electroweak results in Standard Model fits performed by the LEP Electroweak Working Group [9]. The right plot in Figure 6 shows the $\Delta\chi^2$ curve resulting from these fits giving $m_{\rm Higgs} = 76^{+33}_{-24}$ GeV/c^2 at the minimum and a 95% confidence level upper limit of 144 GeV/c^2 which increases to 182 GeV/c^2 when the

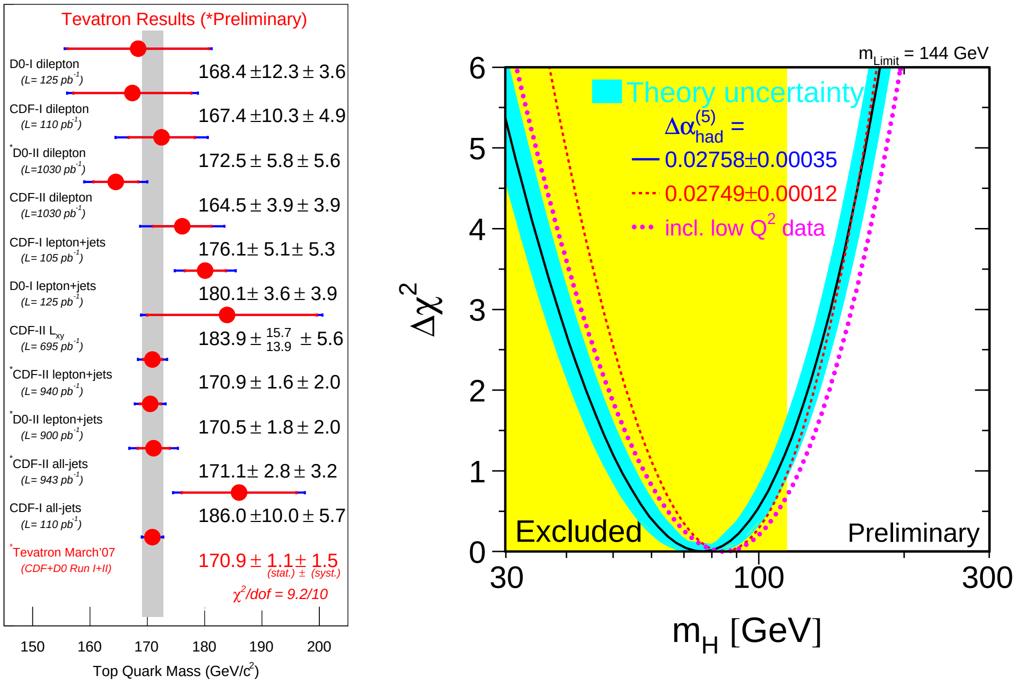

Figure 6: New world average $m_{\rm top}$ and Standard Model fits.

LEP-2 direct search limit of 114 GeV/c^2 indicated by the yellow band is included.

6 Summary and Conclusions

A precise determination of the top quark mass is crucial for constraining the mass of the Higgs boson. Despite the great challenges involved, precise measurements are possible through the use of sophisticated measurement techniques. This talk presented new results based on up to 1 fb^{-1} of data collected by CDF and DØ. Although these results are still dominated by the ℓ+jets channel, the other two show promise and we hope to see more competitive results from them in the future. Combining the new results with previous ones has yielded a new preliminary world average top quark mass with a total uncertainty of 1.8 GeV/c^2 and imposed new constraints on $m_{\rm Higgs}$. As more data become available at the Tevatron, we can expect statistical uncertainties < 1 GeV/c^2 by the end of the Tevatron run at which point the total uncertainties will become dominated by the systematic uncertainties.

References

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